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Dynamic inflatable, friction rockbolt for deep mining

F Scolari *DSI Underground GmbH, Germany*

M Brandon *DSI Underground GmbH, Germany*

H Krekula *Northern Mining Products AB, Sweden*

Abstract

DSI Underground developed a bolt, based on a frictional, inflatable bolt combined with an internal additional load-bearing element, called the Dynamic Omega-Bolt. This paper provides technical detail of the bolt design and the results of laboratory tests of its performance. Laboratory drop tests conducted at the CanmetMINING laboratories suggest that under dynamic loading, the bolt exhibits a peak tensile strength based on the frictional element combined with a residual loading capacity from the internal element. Failure of both elements of the bolt corresponds to an average absorption of 35 kJ of energy due to steel elongation. The residual loading capacity is in the range of 70 kN and it is intended to retain the dead load of broken rock slabs generated by an event of a sudden release of energy, as long as sufficient friction bond length is retained at both ends of the bolt. The Dynamic Omega-Bolt associates the well-known advantages of inflatable friction bolts such as fast, clean and safe installation, with an improved capacity of energy/deformation absorption from the internal point anchored element.

Keywords: *dynamic rockbolts, inflatable friction bolts, omega rockbolts, dynamic rock reinforcement*

1 Introduction

The behaviour of inflatable, friction rockbolts under a sudden energy release was initially investigated by Ortlepp and Stacey (1998), testing small sized, 2 mm thick steel wall, inflatable bolts with ultimate tensile strength of 120 kN. More recently Player et al. (2009) tested larger sized inflatable bolts, featuring 3 mm thick steel wall and 240 kN ultimate tensile stress, a value considered more suitable for deep underground mining. Being manufactured by ductile and heat-treated steel, this bolt type delivers an elongation higher than 20%. The results obtained using the Western Australian School of Mines dynamic test facility showed an average energy dissipation of 6.2 kJ/100 mm of slip normalised per metre of embedment. The same paper indicates that axial sliding velocities of up to 3.5 m/s were stabilised by these types of bolts. The general behaviour of inflatable friction bolts is plotted in comparative diagrams by Potvin et al. (2010).

The damages caused by seismic events at the Luossavaara-Kiirunavaara Aktiebolag (LKAB) Kiruna Mine, described in Woldemedhin and Mwagalanyi (2010), raised concerns about the unsatisfactory performance of traditional ('static') grouted bars, cables, as well as inflatable rockbolts in case of dynamic load caused.

As a consequence of these events, Kiruna Mine initiated large scale, in situ tests of dynamic rock support systems as reported by Shirzadegan et al. (2016). This tests focused on the response of reinforced test mine wall under a dynamic load, and evaluate the performance of different types of rockbolts. In particular, for high ductility inflatable bolts, rated 240 kN ultimate tensile strength, the authors indicate a measured energy absorption level of 17 kJ, obtained at 80 mm deformation.

This level of energy absorption is not considered fully satisfactory by LKAB, requiring a dynamic energy absorption of a minimum of 30 kJ, measured according to Canmet drop test, split tube set-up (Swedberg at al., pers. comm., 2016).

In order to provide increased energy absorption for commonly used inflatable friction bolts, Håkan Krekula and Leif Eriksson, two rock reinforcement specialists operating in Northern Sweden, started combining a point anchored support element with an inflatable friction bolt. Their work resulted in a concept, series of prototypes and finally in the patent WO2013002711 (Krekula & Eriksson 2013).

Expandable friction rockbolts are used to stabilise a variety of rock types and in different stress conditions. These bolts are based on a steel tube, longitudinally formed with welded bushings on each end. A high-pressure water pump, able to provide up to 300 bar, is used to expand the profile to tightly fit within a rockbolt hole. The confinement from the surrounding rock creates a tight, mechanical interlock between the steel profile and the rock.

The new dynamic bolt features an additional steel element (Figure 1), which is located inside the omega shaped profile and welded to the upper and lower bushings. This new, de-bonded, point anchor load-bearing element provides additional loading capacity in static conditions with the capacity to absorb a large quantity of elastic energy.

Figure 1 Main components of a Dynamic Omega-Bolt. The additional load-bearing element has a typical 'C' shape, perfectly integrated in the internal cavity of the traditional 'Ω' profile

The bolt has been developed to provide safe, effective and fast rock support in underground excavations, mines or tunnels, where high stress in the rock mass can create a sudden release of energy (e.g. rockbursts, bucking, spalling). Sudden releases of energy are difficult to predict and they represent a great danger to miners and equipment. A good preventive measure is the installation of a rock reinforcement system suited for dynamic loading conditions. This can take the form of a combination of support elements to absorb the dynamic energy while maintaining support capacity for the dead weight of loose rock such as rockbolts, steel mesh and shotcrete (Figure 2).

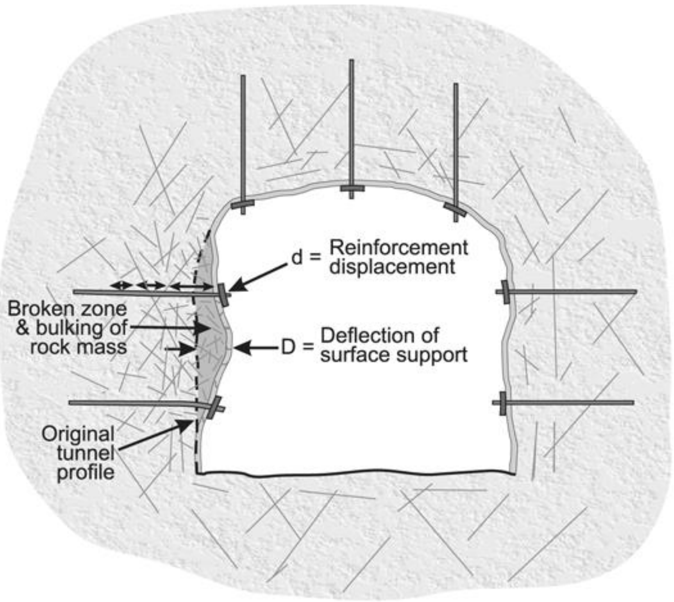

Figure 2 Schematic showing the combination of reinforcement elements (rockbolts) and surface confinement (shotcrete, wire mesh, lacing) (Potvin et al. 2010)

2 Principles of functioning in static conditions

All rockbolts are intended to help the rock mass become self-supporting by inter-linking broken parts (bridging joints and cracks) and by improving the global stability behaviour (controlled stress/strain development). When an inflatable friction bolt is installed in a pre-drilled hole, high-pressure water is used to expand the steel profile to achieve high friction and a mechanical interlock with the surrounding rock. The result is that the entire length of the bolt is well-anchored to the rock and is able to develop a frictional resistance to sliding. Steel grade and heat treatment can deliver stiffer or more yielding bolts. In order to withstand (absorb) an energy shock created by a rockburst, Dynamic Omega® features an additional, unbonded, 'C' formed profile (Figure 3), which is point anchored to the bushings at both ends of the bolt. This design allows for the elongation of the complete bolt length for increased energy absorption capacity.

Figure 3 The additional load-bearing element is located inside the traditional inflatable friction bolt profile so it is not in contact with surrounding rock

The external inflatable friction bolt profile is frictionally engaged with the surrounding rock, and its mechanical behaviour has been well documented (Stillborg 1994). During a tensile stress test, which simulates a crack between two blocks, the load in the bolt rapidly increases to a point where the steel profile decreases creating a local 'de/bonding', i.e. a steel detachment from surrounding rock. This phenomenon allows significant deformation (in the range of 40–50 mm) before breaking. The allowable deformation will increase in weak rock masses and decrease in strong rocks. The correct selection of steel grades with appropriate yielding proprieties can optimise the load/displacement performance.

This paper presents a specific version of a dynamic inflatable bolt, where both outer profile and inner element are manufactured by a 2 mm thick steel plate. Its denomination is Dynamic Omega-Bolt® 35 and the outer profile has a steel cross-section of 326 mm² and loading capacity of 160 kN and the internal 'C' element has an ultimate tensile load of 70 kN and a cross-sectional area of 154 mm². The additional internal 'C' element is not in direct contact with the rock and the load will be transferred to it only due to the total deformation of the external friction component. The internal profile yields along its total length since it is point anchored. Based on the grade of steel used for the point anchored element, an elongation of > 15% can be expected. For a 3 m bolt length, the point anchored component can undergo more than 450 mm of elongation prior to failure. The internal and external elements cooperate to reach the maximum peak load, however, the external profile reaches its breaking point first, while the internal element remains intact. Figure 4 shows the load deformation profile of the two elements of the bolt.

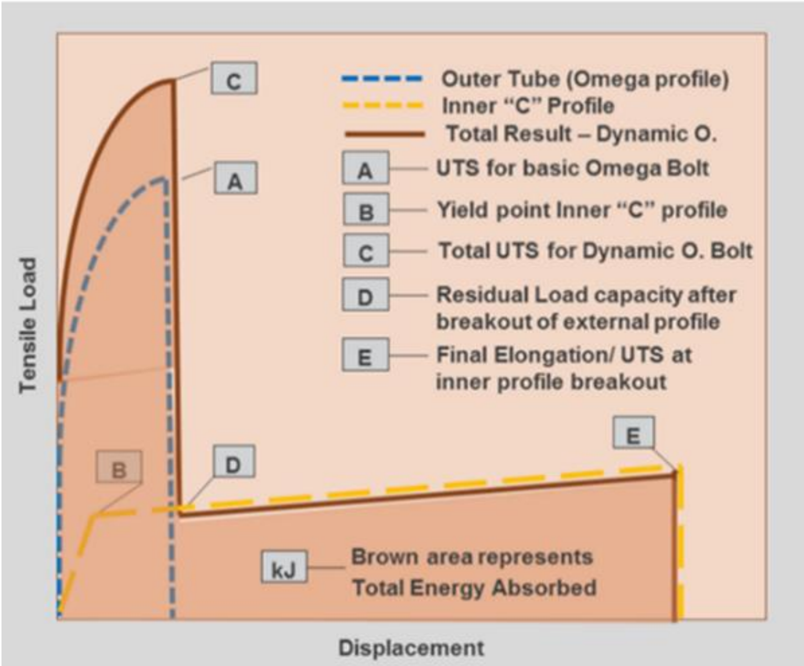

Figure 4 **Conceptual diagram showing the interaction between internal and external elements of a Dynamic Omega-Bolt. The simplified load–displacement curve refers to a tensile test across a simulated transversal crack (Lindback, pers. comm., 2013)**

A recent session of static tests performed at Canmet just confirms the behaviour indicated by the analytical model. In particular, Figure 5 confirms that both internal and external profiles get loaded and deliver the sum of their theoretical loading capacity. Figure 6 shows the sequence of breaking mechanism, the cracking points and the elongation registered.

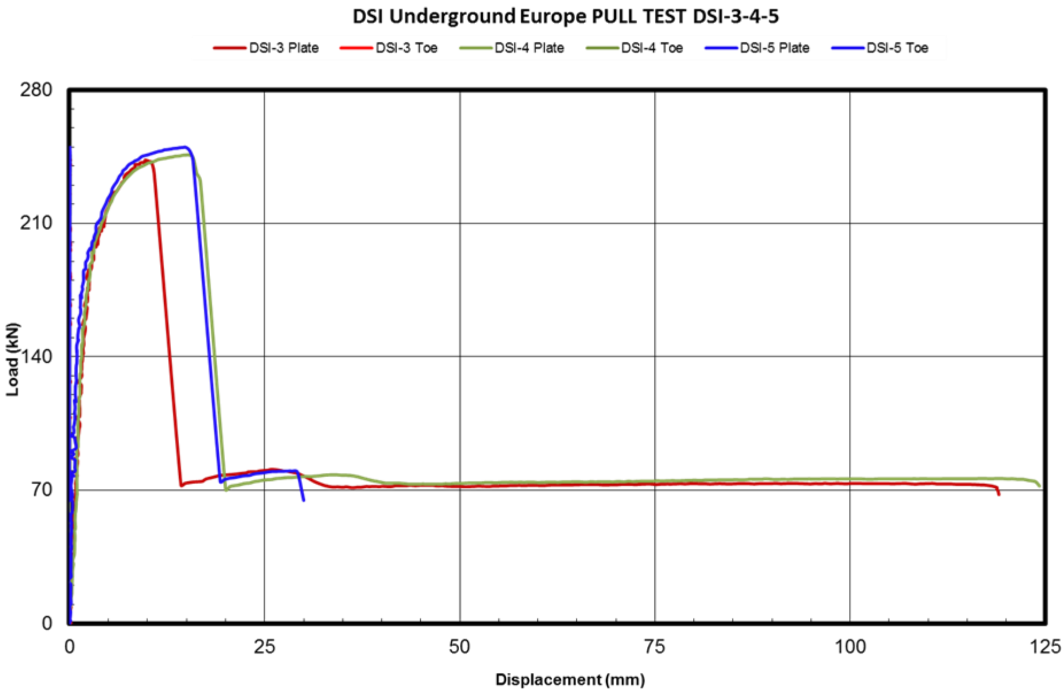

Figure 5 **Results of static 'continuous tube' pull test. In this case, the load is applied to the face plate, and via tis to a 2.1 m long inflatable dynamic bolt inserted in a continuous rock sample. Note in this diagram the x-axis represents time is seconds (Canmet, pers. comm., November 2016)**

Figure 6 On the left the moment in which outer profile reaches the breaking load. Of the right the final status of the bolt, after final breaking point. Note the outer profile displacement and its breaking surface, located inside the bushing (very close to welding). The inner 'C' element shows a longer elongation (Canmet, pers. comm., November 2016)

Table 1 resumes the results obtained in this session of static pull-out test.

Table 1 Summary of static pull-out tests performed, continuous tube set-up, performed at Canmet laboratory (Royer, pers. comm., 2016)

Specimen	Yield load (kN)	Max. load (kN)	Failure load-outer profile (kN)	Failure load-inner profile (kN)	Plate displ. (mm)	Toe displ. (mm)	Elongation (mm)
DSI-3	200	243	236 @ 11 mm	68	119	0.2	119
DSI-4	237	246	232 @ 17 mm	72	124	0.1	124
DSI-5	180	250	243 @ 16 mm	64	30	0.1	30
Average	**206**	**246**	**237 @ 14 mm**	**68**	**91**	**0.1**	**91**
Std dev.	29	3.4	5.6 @ 3.2 mm	4	53	0.1	53

3 Dynamic behaviour: Canmet drop test results

The dynamic behaviour of the Dynamic Omega-Bolt 35 has been tested by Canmet, a qualified Canadian public institution. Figure 7 shows a 'split tube drop test' used to simulate a single crack in the surrounding rock. Tests on 2.4 m long Dynamic Omega-Bolts 35 were conducted by Canmet, using the 'split tube' set-up. The test procedure is conducted on an anchor installed in two rock samples, laterally confined by a heavy steel pipe and a dynamic load created by a dead weight falling from a set height and impacting the face plate. Load and displacement are continuously measured both at rockbolt's top and at its bottom end (face plate). This procedure has been applied to a wide range of resin or cement grouted bolts, as well as friction bolts, becoming an important benchmarking test method for any support element facing natural sudden releases of energy.

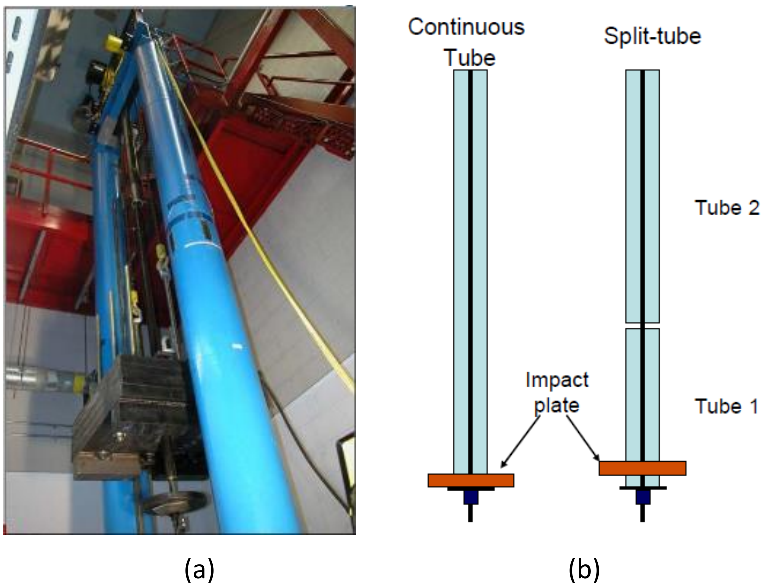

Figure 7 (a) Photo of CanmetMINING's drop test rig; and (b) 'continuous' tube and 'split tube' configuration (after Doucet 2012)

The Dynamic Omega-Bolt 35 was tested with an impact of 29.5 kJ and the results verify the support mechanism described in this paper (Figure 8).

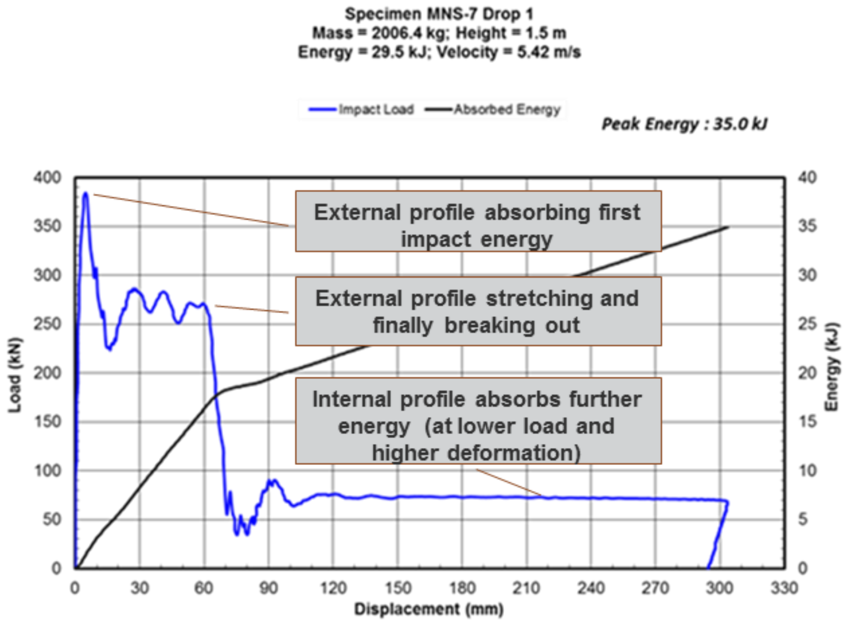

Figure 8 Typical load–displacement curve for dynamic inflatable friction bolts subjected to a drop test with 29.5 kJ impact and in 'split tube' configuration

The tests demonstrate that, under dynamic load conditions, the dynamic inflatable friction bolt maintains the expected 'two phase' behaviour, with a peak loading capacity and a residual load capacity. The contribution of the external, fully bonded, frictional element is clearly visible in the initial part of the curve. The bolt reached the peak load (369 kN) after minimal deformation and then yielded for approximately 60–80 mm before failure. The point anchored component of the bolt remained intact for a total deformation of approximately 300 mm, absorbing about 50% of the total elastic energy of the bolt. The results are within the design limits of the bolt for the 2.4 m length. The results of split tube drop tests are summarised in Table 2. Table 3 gives the technical specifications for the bolts tested.

Table 2 Results of dynamic drop tests, 'split-tube' configuration, performed at CanmetMINING (Royer, pers. comm. 2016). Bolts NMS-5 and NMS-7 survived the first drop and received a second impact

Drop number	Impact energy kJ	Top displacement mm	Plate displacement mm	Steel elongation % of strain	Impact peak load (kN)	Absorbed energy (kJ)
NMS-5 -1	29.52	5	388	16.1	369.48	37.09
NMS-5-2	19.68	Failed	17	0.7	166.15	0.84
NMS-6-1	29.52	0	351	14.5	368.9	34.67
NMS-7-1	29,52	0	294	12.2	216.18	34.89
NMS-7-2	19.68	-	1	4.16	53.69	10.07
Average			**344**	**14.29**	**374.1**	**35.6**
Std. dev.			47	1.95	8.5	1.3

Table 3 Results of dynamic drop test, 'continuous tube' configuration, performed at CanmetMINING (Royer, pers. comm. 2016)

Drop number	Impact energy kJ	Top displacement mm	Plate displacement mm	Steel elongation % of strain	Impact peak load (kN)	Absorbed energy (kJ)
DSI-6 -1	19.03	0	212	8.8	302	22.4
DSI-8-1	19.03	0	200	8.3	312	22.7
DSI-8-2					103	15.6
Average		**0**	**206**	**8.5**	**307**	**22.66**
Std. dev.		0	8.6	0.3	7.5	0.2

In both cases, the outside profile failed, while the inner profile survived the 19.03 kJ impact. In sample DSI-7, inner profile failed at a second drop, at a peak load of 110 kN and a plate deformation of 204 mm. Inner profile of sample DSI-8, failed at a second drop, after a deformation of 773 mm, corresponding to an energy absorption of 15.6 kJ.

The combination of technical data and the results obtained in the two sessions of Canmet laboratory tests are combined in a preliminary technical specification, as illustrated in Table 4.

Table 4 Dynamic Omega-Bolt 35 technical specifications

Dynamic Omega-Bolt 35 kJ	Design parameters/minimum values	Typical values
Steel: yielding/tensile stress	350/ 500 MPa	
Steel elongation (A5)	10%	15%(1)
Steel sheet thickness (inner/outer profiles)	2 mm	
Steel cross-section, outer profile	326 mm²	
Steel cross-section, inner profile	154 mm²	
Bolts mass per metre	3.75 kg/m	
Bolt diameter: installation profile, upper bushing, lower bushing	36/38/41 mm	
Diameter fully expanded profile	54 mm	
Recommended drillhole	45–51 mm	
Static ultimate tensile strength (UTS)	163 + 77 = 240 kN	246 kN
Static shear resistance(2)		85–90% UTS
Dynamic energy absorption (1 drop)		35 kJ(1)
Plate displacement (1 drop)(3)		350 mm(1)

(1) CanmetMINING (Canada) laboratory tests report (2016). Split tube test configuration. (2) SINTEF (Norway) laboratory tests (SINTEF (Norway), pers. comm., 2014). (3) Tests on a 2 and 4 m long bolt.

4 Concluding remarks

The sessions of dynamic drop tests performed at Canmet laboratories confirmed the validity of the concept of adding a point-anchored element to an inflatable friction rockbolt. In particular, this new rockbolt offers an interesting combination of a relatively stiff initial response, followed by a secondary ductile behaviour associated to an improved capacity of energy absorption The specific version of the dynamic inflatable bolt tested at CANMET showed an energy absorption capacity in line with the 30 kJ class of dynamic rockbolts, a level normally considered sufficient for hard rock mines subjected to rockburst, e.g. as indicated by LKAB Technical Inquiry for ductile rockbolts for rockbursts applications (Malmgren, pers. comm., 2013; Swedberg, pers. comm., 2016). Energy absorption measured (35 kJ) and plate deformation (in average 350 mm), position this new friction bolt within the cluster of 'yielding support' as indicated by Potvin et al. (2010). The position of new dynamic inflatable bolt is displayed in Figure 9.

'Continuous tube configuration' tests performed at Canmet in Q4 2016, measured the rockbolt's performance at its lower end (close to the ace plate). The static test confirmed the validity of the analytical model, with a peak tensile strength of 237 kN in average, and a residual tensile strength (inner element) of average 68 kN. The dynamic test indicated that this dynamic inflatable bolt is able to absorb in average a dynamic energy of 22 KJ.

Two series of static pull tests performed during November and December 2016, respectively at LKAB Malmberget mine and at Outokumpu Kemi mine, were able to confirm and validate the static behaviour of this dynamic inflatable bolts and the values measured at Canmet laboratory.

The enhanced dynamic behaviour of this new concept expands the application field of inflatable to deep mines. For instance, its static and dynamic performances in line with LKAB technical requirements for a ductile rockbolt for rockburst applications.

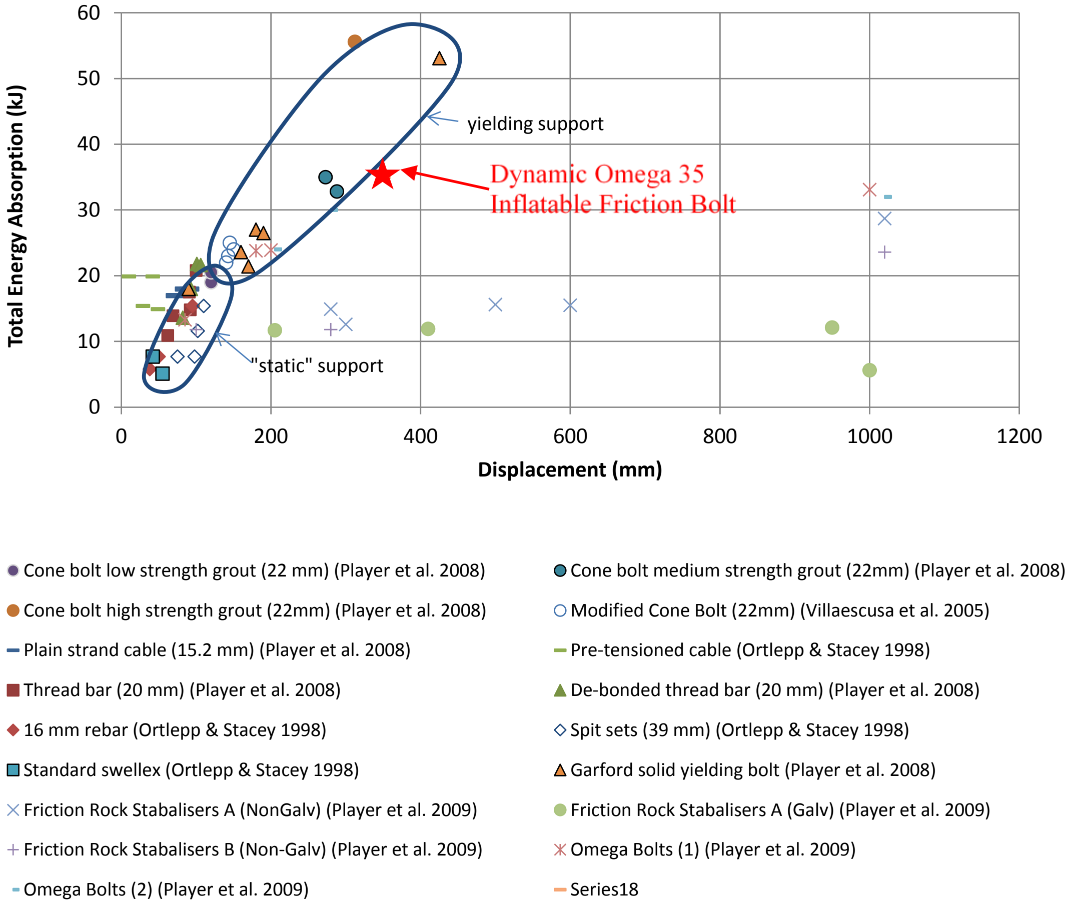

Figure 9 Compilation of drop tests performed on various reinforcement elements (modified after Potvin at al. 2010). The position of the new, dynamic inflatable rockbolt (corresponding to 35 kJ at 350 mm displacement) is added (see the red star)

Acknowledgement

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